Summary of Forum 2008 Findings on Microlensing

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April 21, 2009 Missions for Exoplanets

Microlensing Peculiarities

- Microlensing planet community is comparatively small and collaborative.
- General consensus (and movement) on forward directions.
- Two primary paths forward
  - Ground based, 1-5 years
    - Frequency of planets $>M_\oplus$ beyond the snow line.
  - Space based, 5-10 years, ~$300M
    - Complete census of planets with mass greater than Mars and $a > 0.5$ AU, including habitable planets and free floating planets.
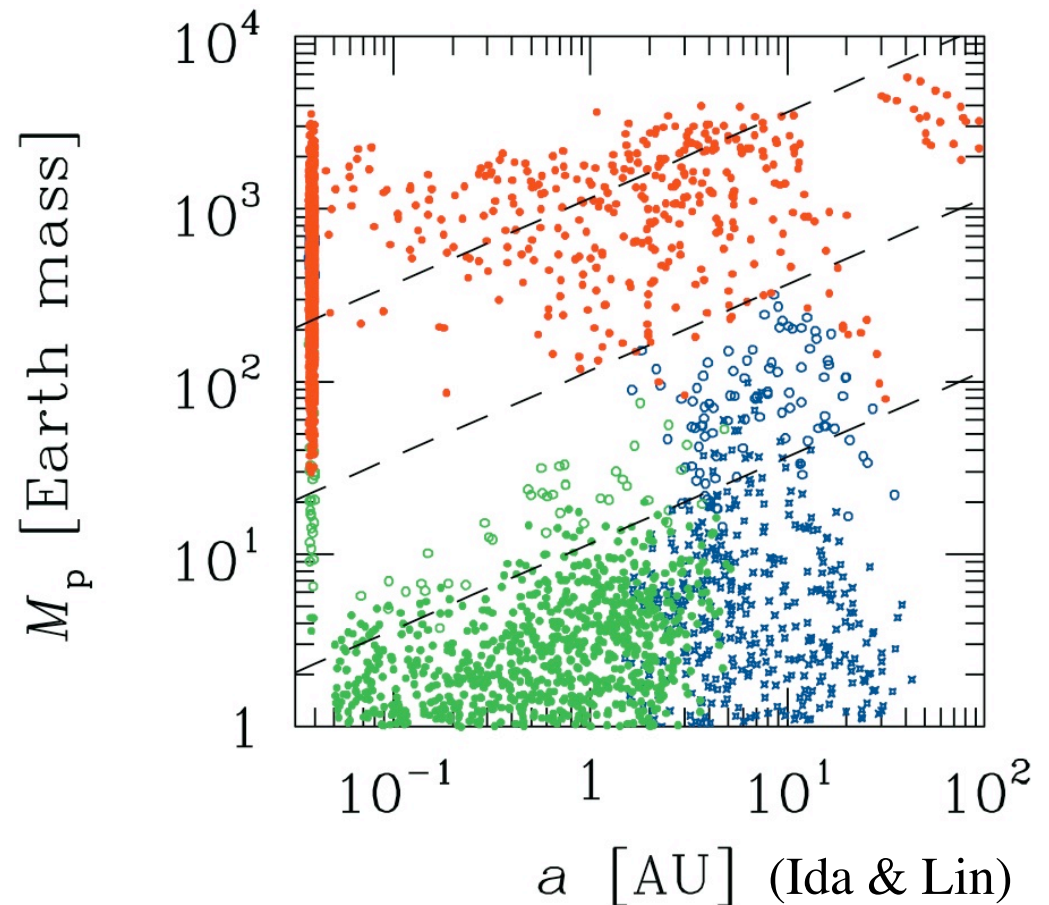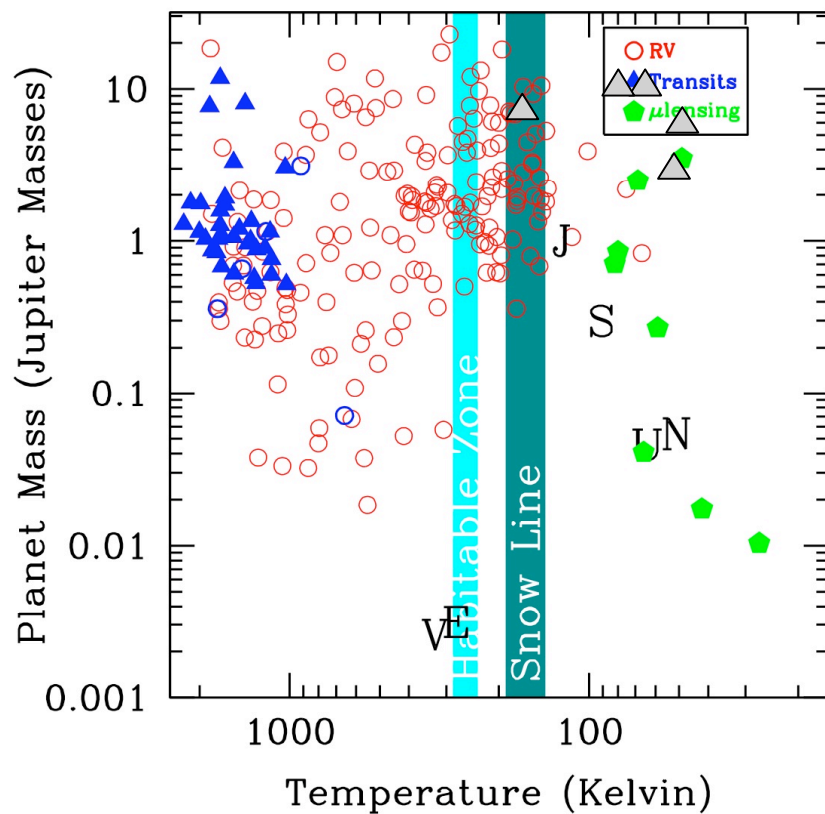
Beyond the snow line:

- Location of giant planet formation (and our giant planets).
- 'Failed Jupiters'
- Source of water

Ground-based μlensing surveys probe planets with $M>M_{\oplus}$ beyond the snow-line.

Exoplanet Discovery Potential
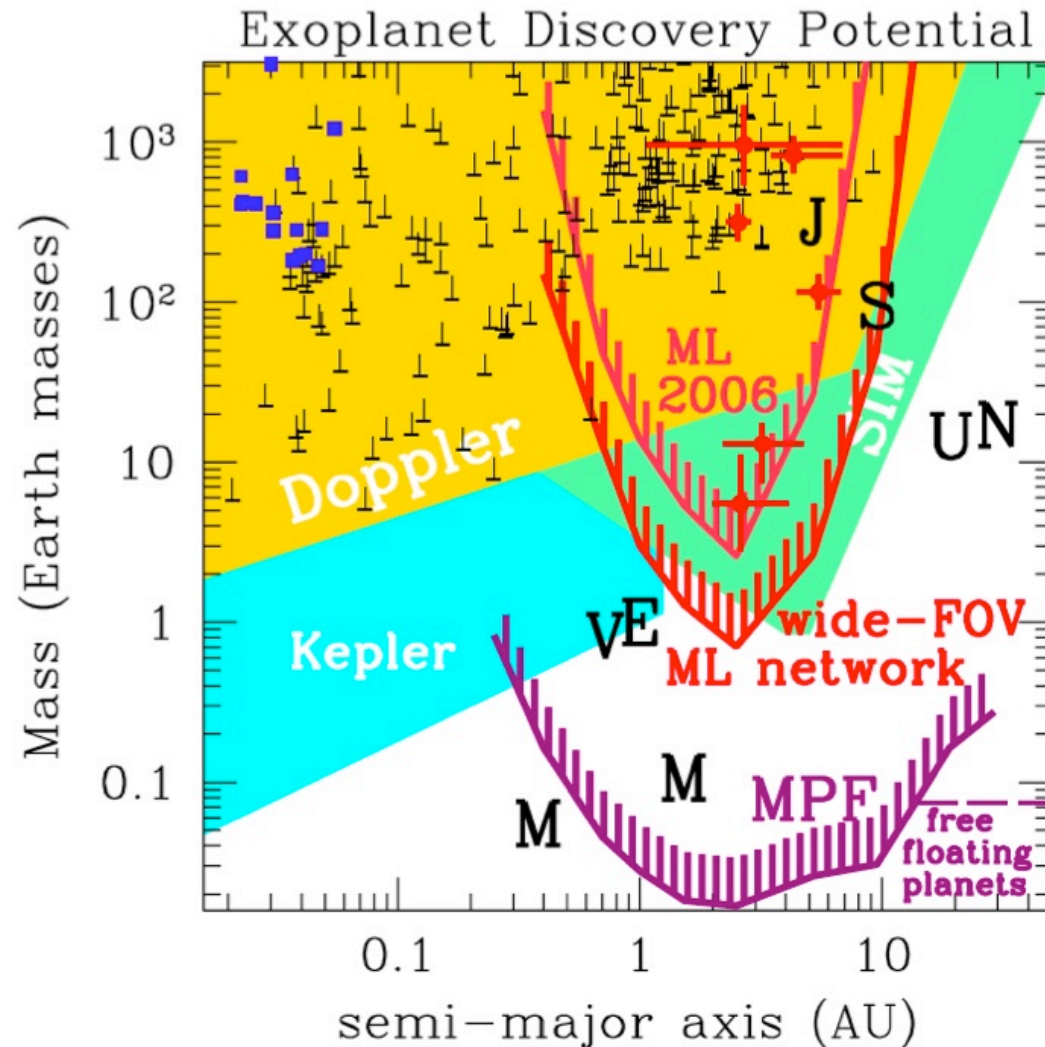
A space-based survey will provide a complete census of planetary systems with mass greater than Mars and a>0.5 AU (from 0 to ∞ with Kepler), including habitable planets.
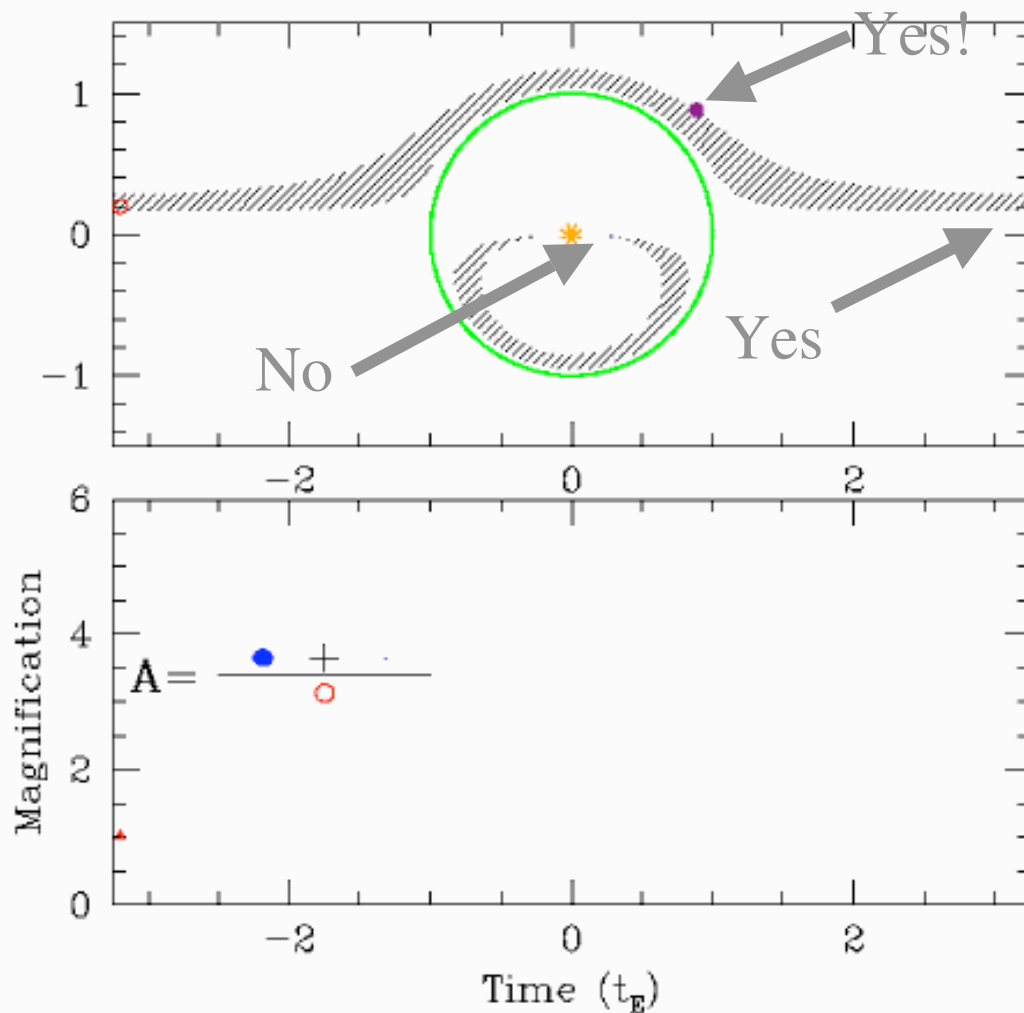
Detecting Planets
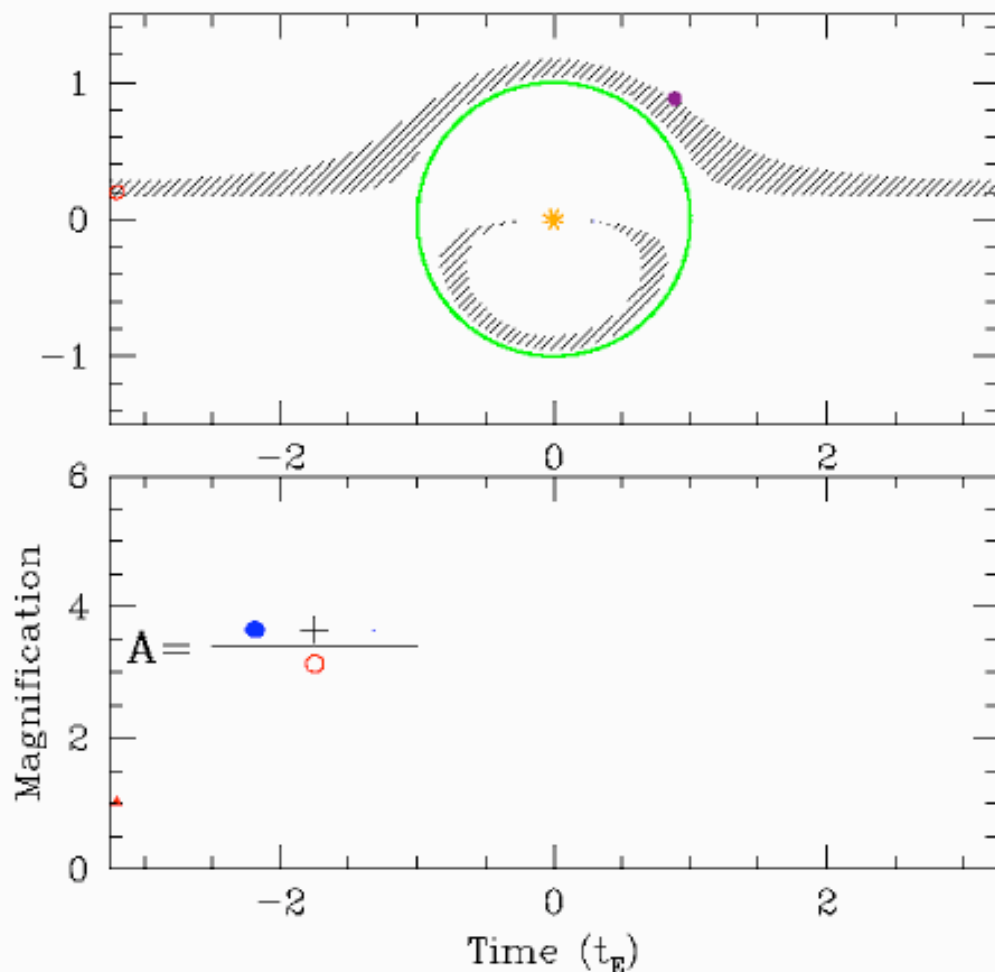
Primary event:
- Smooth, symmetric
- Typically 20 days

Planetary perturbation to images
- Short-timescale bump
- Measure:
  - Projected Separation
  - Mass Ratio

$$t_p = q^{1/2} t_E \approx 1 \text{ day} \left(\frac{M_p}{M_J}\right)^{1/2}$$

Microlensing is directly sensitive to planet mass

- Works by perturbing images
- Does not require light from the lens or planet.
- Sensitive to planets in the disk and bulge with D_{OL}=1-8 kpc
- Most sensitive to planets near the Einstein radius
- Sensitive to wide or free-floating planets
- Not sensitive to very close planets

Very Low Mass Planets

Signal magnitude is *independent* of planet mass.
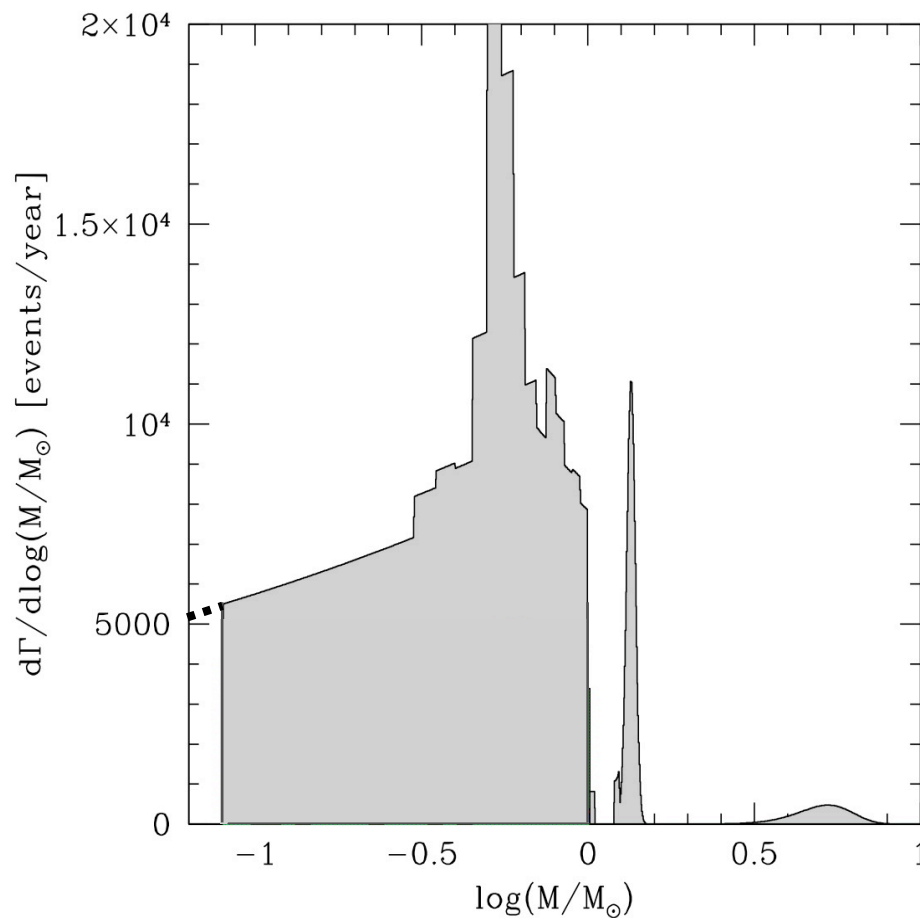

Bennett & Rhie
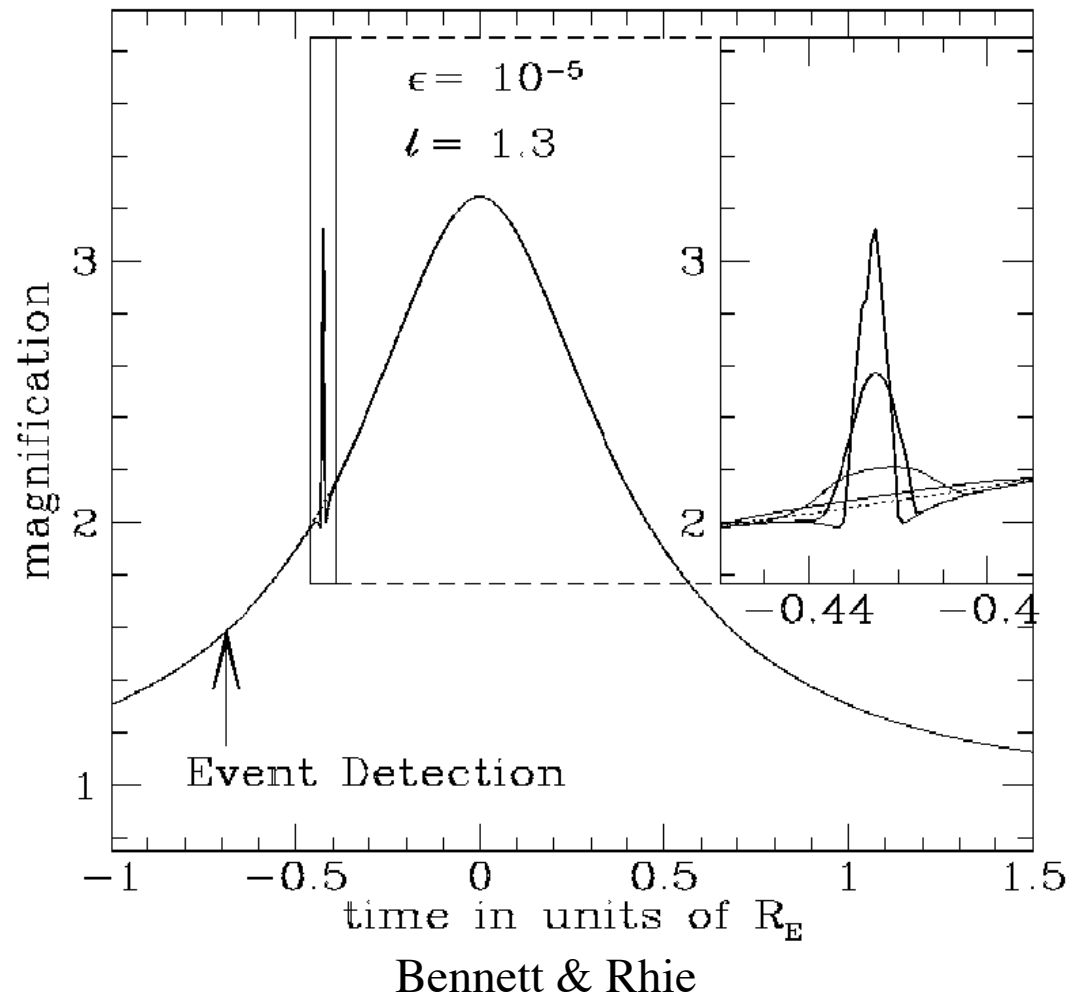
- Magnitude depends on separation of planet from image.
- Duration depends on mass.

$$t_p = q^{1/2} t_E \approx 2 \text{ hrs} \left(\frac{M_p}{M_\oplus} \right)^{1/2}$$

- Signals get rarer and briefer.
- Detection Probability ~ few %
- Large signals for low-mass (Earth-mass) planets
- **Sub Mars-mass planets detectable**

Sensitivity Depends Weakly on Host Mass

Sensitive to planets around:

- Main-sequence stars with $M < M_\odot$

- Brown dwarfs

- Remnants

Microlensing Strengths

- Peak sensitivity beyond the snow line.
    - 50-100K
- Sensitivity down to *very* low-mass planets.
    - Mass greater than that of ~10% Mars.
- Sensitivity to long-period and free-floating planets.
    - 0.5 AU - ∞
- Sensitivity to planets over a wide range of host masses.
    - $M < M_\odot$
- Sensitivity to planets throughout the Galaxy.
    - 1-8 kpc
- Sensitivity to multiple-planet systems.

Commonly Heard Complaints…

- **But you don't know anything about the star, orbits, etc!**

  — Typically can measure host star and planet masses to ~10-20%.

  — In some special cases can learn something about the orbit.

- **But the systems are so far away and faint!**

  — Sufficiently bright to measure flux, color, and in some cases get spectra.

- **But you only see it once!**

  — Signals are large and unambiguous.
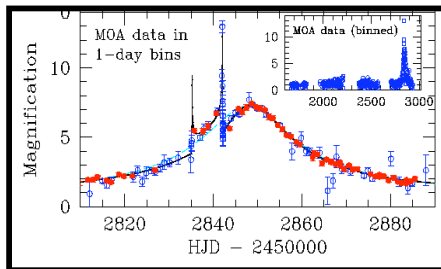
- **Demographics of planetary systems.**

First Four Detections.

OGLE-2005-BLG-071
(Udalski et al 2005)
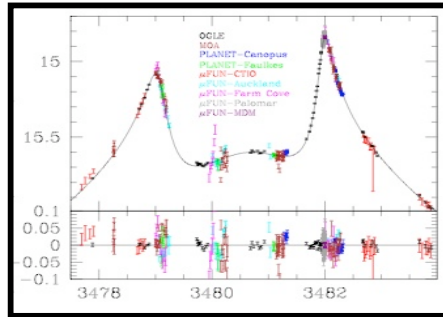
$M_p \sim 3.5 M_J, \ r \sim 3.6 \text{AU}$
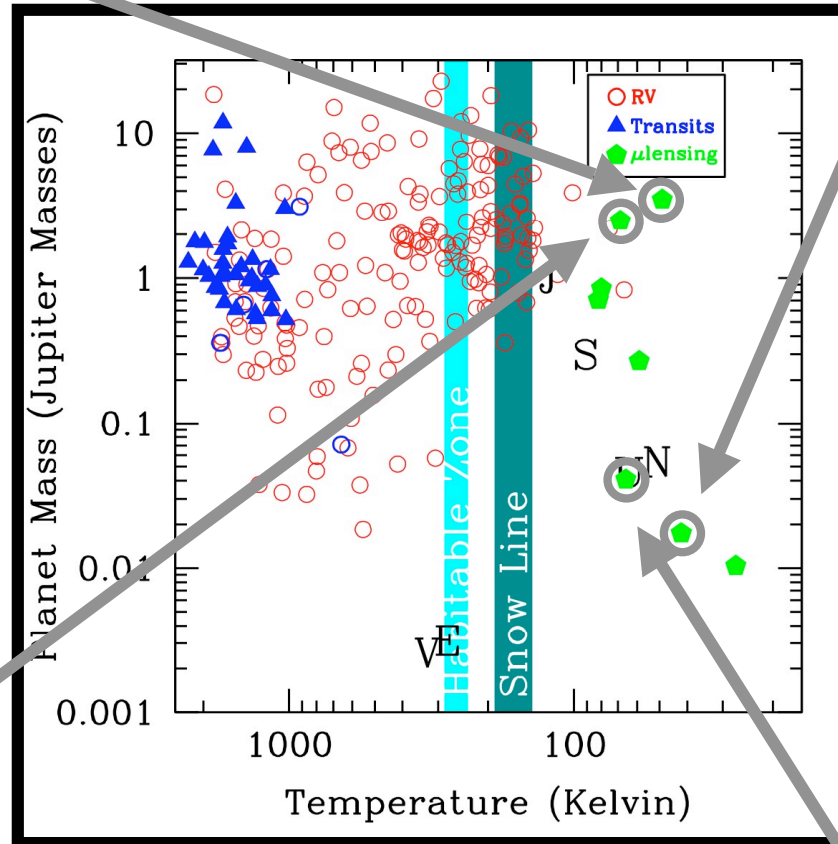
$M_* \sim 0.46 M_\odot, \ D_{OL} \sim 3.3 \text{ kpc}$

OGLE-2005-BLG-390
(Beaulieu et al 2006)

$M_p \sim 5.5 M_\oplus, \ r \sim 2.6 \text{AU}$

$M_* \sim 0.22 M_\odot, \ D_{OL} \sim 6.6 \text{kpc}$

OGLE-2004-BLG-235
MOA-2004-BLG-53
(Bond et al 2004)
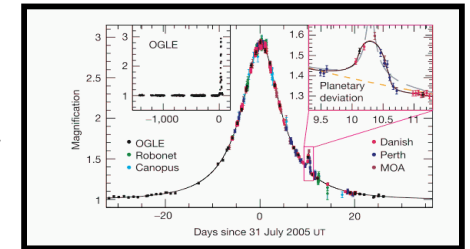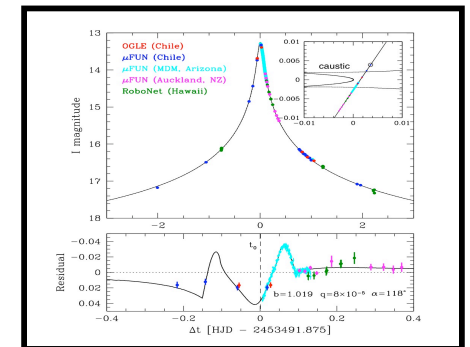

$M_p \approx 2.5 M_J, \ r \approx 4.3 \text{AU}$

$M_* \sim 0.65 M_\odot, \ D_{OL} \sim 6.5 \text{kpc}$

OGLE-2005-BLG-169
(Gould et al 2006)

$M_p \sim 13 M_\oplus, \ r \sim 3.5 \text{AU}$

$M_* = 0.5 M_\odot, \ D_{OL} = 2.7 \text{kpc}$

Two Jovian-mass planets
Two "Super Earth" planets

Cool "Super Earths" Are Common.

Two low-mass detections imply:

~20% of stars have Super Earths between 1.6-4.3 AU (10-30%)

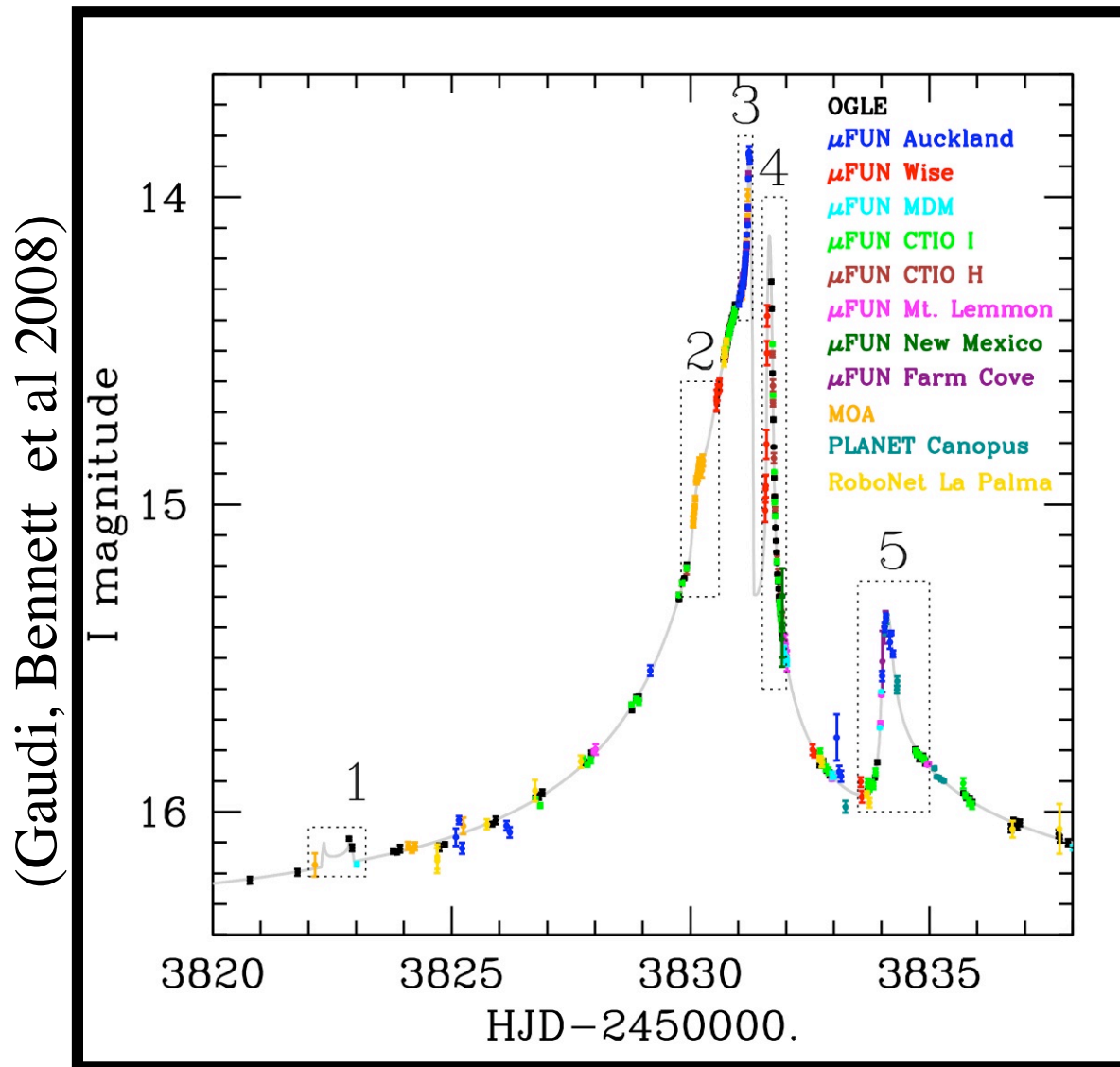**dN/dloga ~ 0.5** at **~3 AU** (0.4-1.6 at 90%)
dN/dloga ~ 0.3 at **~0.15 AU** (Mayor et al 2009, HARPS)

Also:

Cool Super Earths are more common than cool Jupiters

Multiple System

(Gaudi, Bennett et al 2008)

- **High-magnification Event**
  - µFUN, OGLE, MOA

- **Must include two planets, finite source, orbital motion, and parallax**

- **Yields full star and planet masses, information on orbital speed of Saturn and inclination!**

A ~0.5M$_\odot$ late K-dwarf at ~1.5 kpc

The OGLE-2006-BLG-109L Planetary System

Planet b:

Mass = 0.71 ± 0.08 M$_{\text{Jup}}$

Semimajor Axis = 2.3 ± 0.2 AU

Planet c:

Mass = 0.27 ± 0.03 M$_{\text{Jup}}$ = 0.90 M$_{\text{Sat}}$

Semimajor Axis = 4.6 ± 0.5 AU
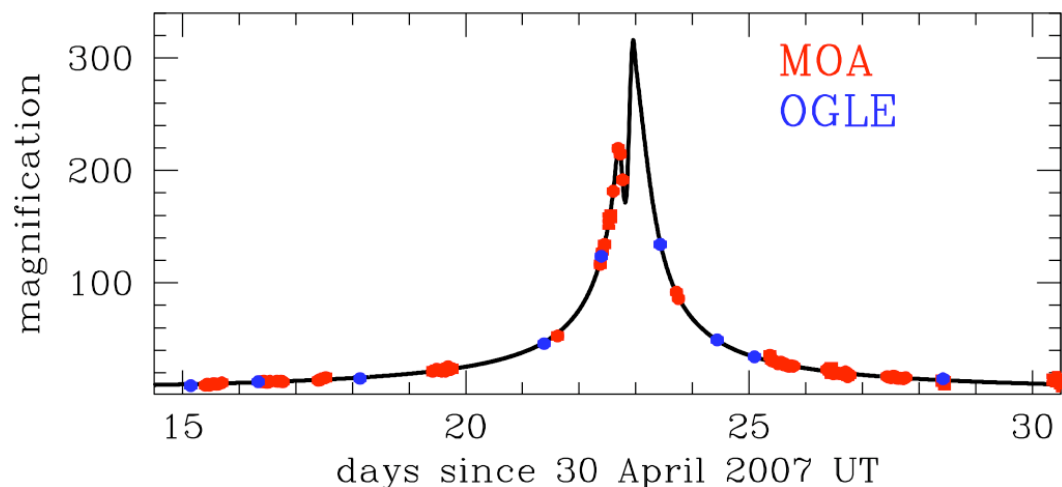
Analog of Jupiter/Saturn
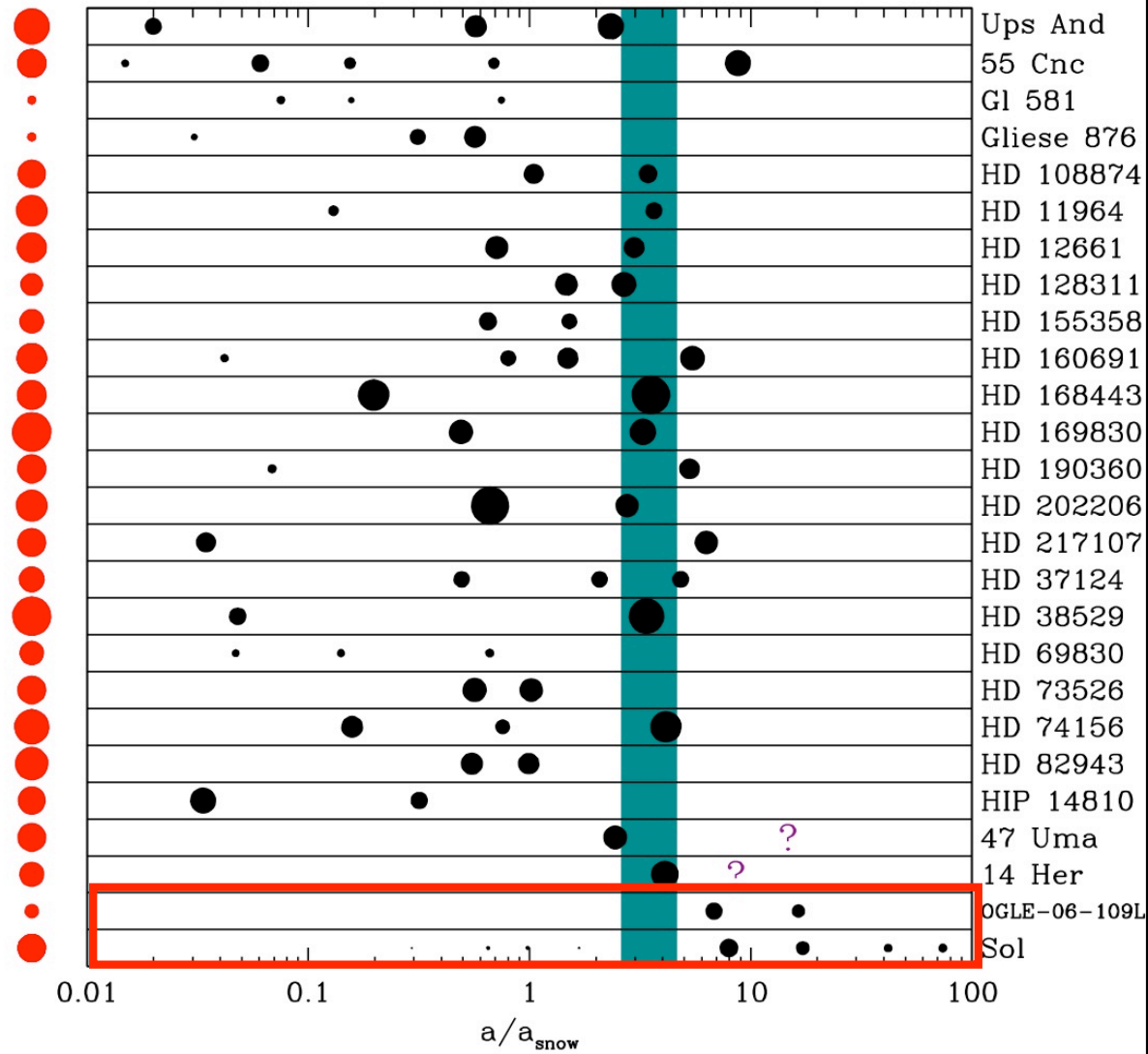
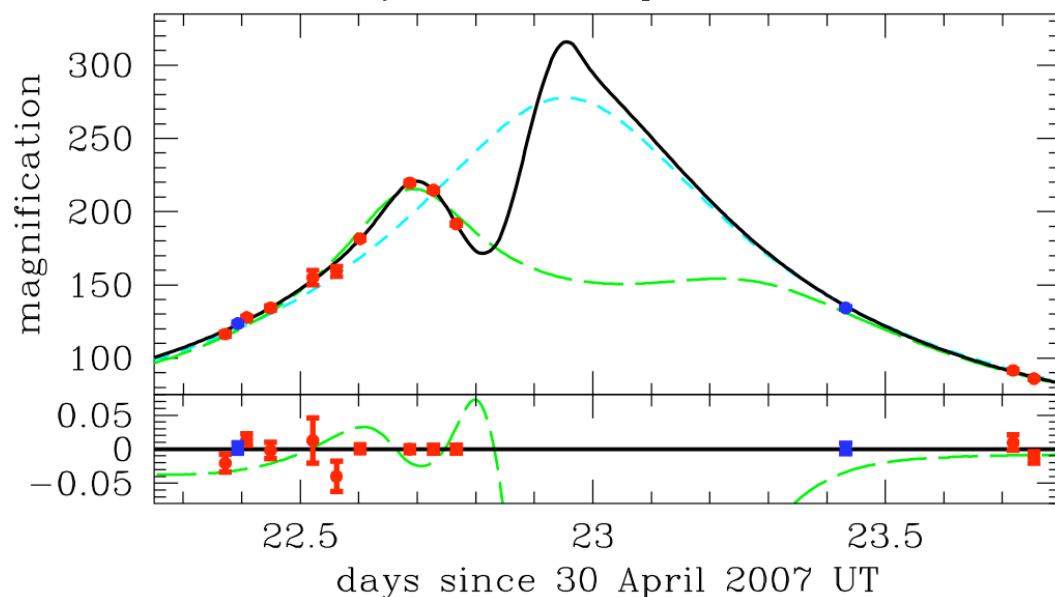# Low Mass Planet Orbiting a Subsstellar Host

$$M = 0.06 \pm 0.03 M_\odot$$

$$m = 3.3^{+4.9}_{-1.6} M_\oplus$$

(Bennett et al 2008)

The Most Massive M Dwarf Planet?
(Dong et al 2008)
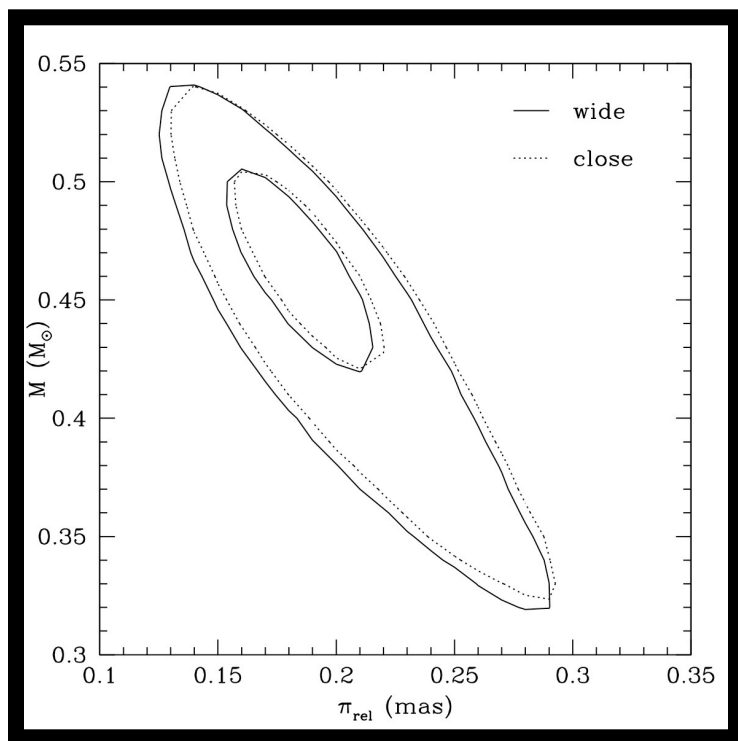
Dong et al. 2008
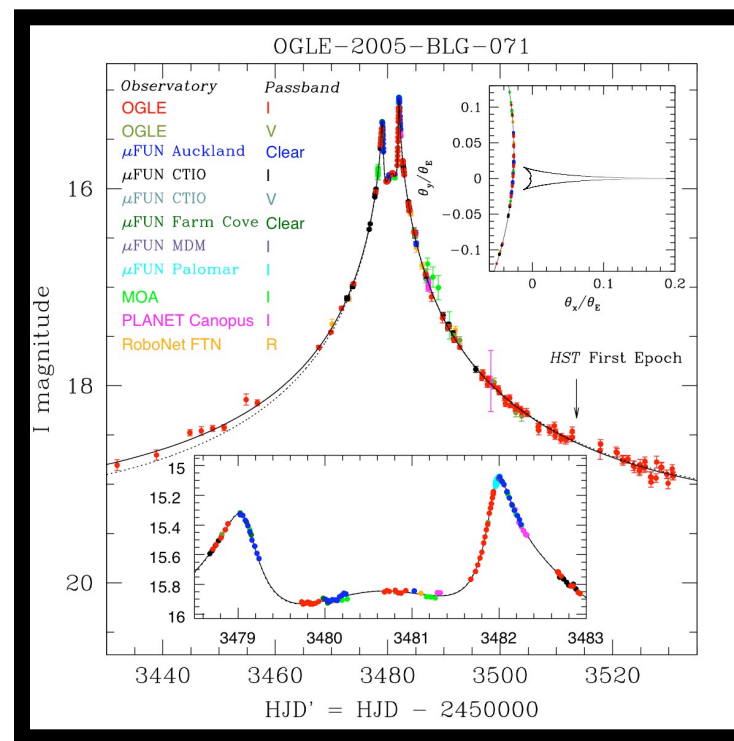
$$M = 0.46 \pm 0.04 \, M_{\odot}$$

$$D_l = 3.3 \pm 0.4 \text{ kpc}$$

$$v_{\text{LSR}} = 103 \pm 14 \text{ km s}^{-1}$$

$$m = 3.5 \pm 0.3 \, M_{\text{Jup}}$$

$$r_{\perp} = 3.6 \pm 0.2 \text{ AU}$$

$$T_{eq} \sim 50K$$

More planets.
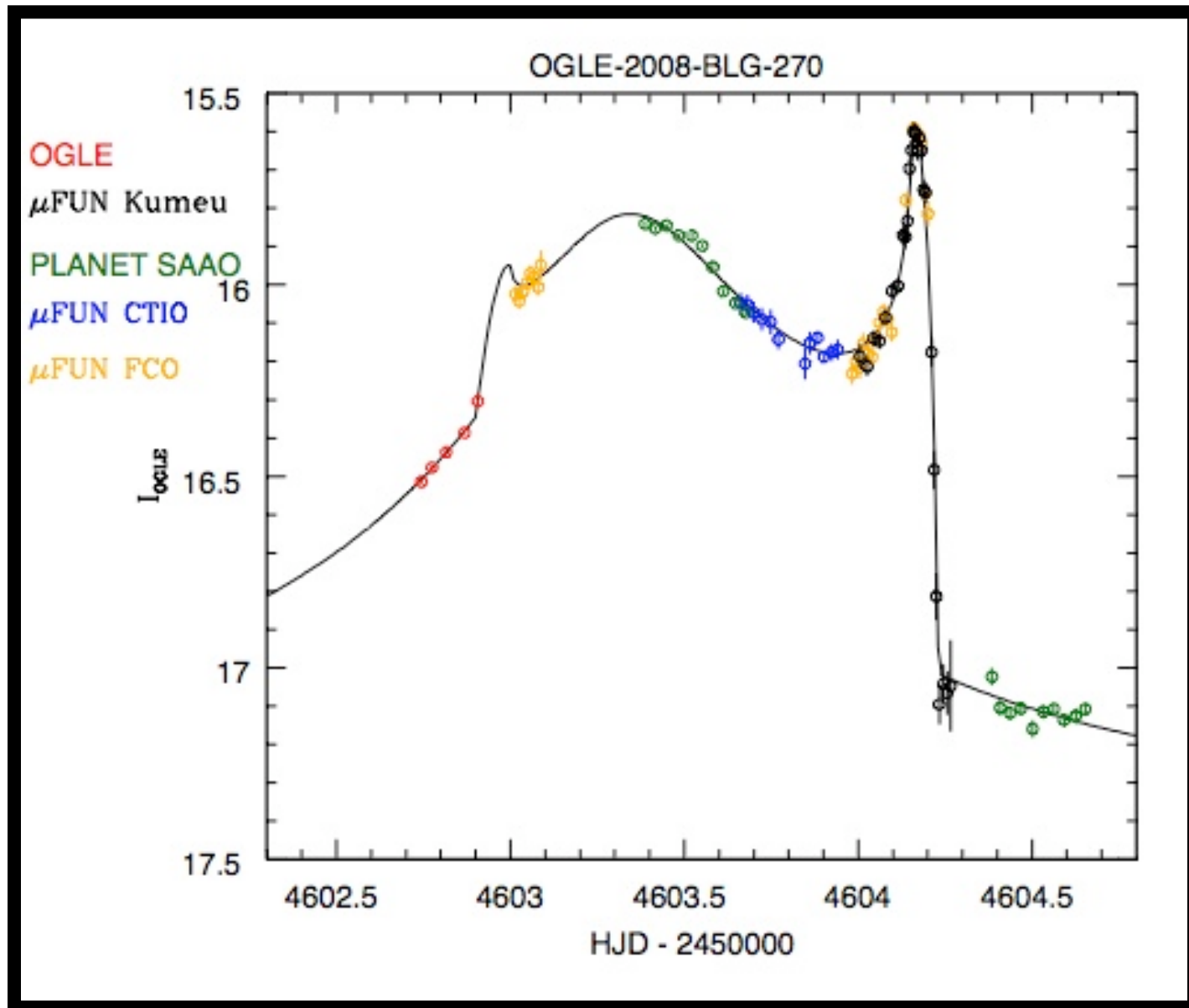
2008: Jupiter-mass planet.
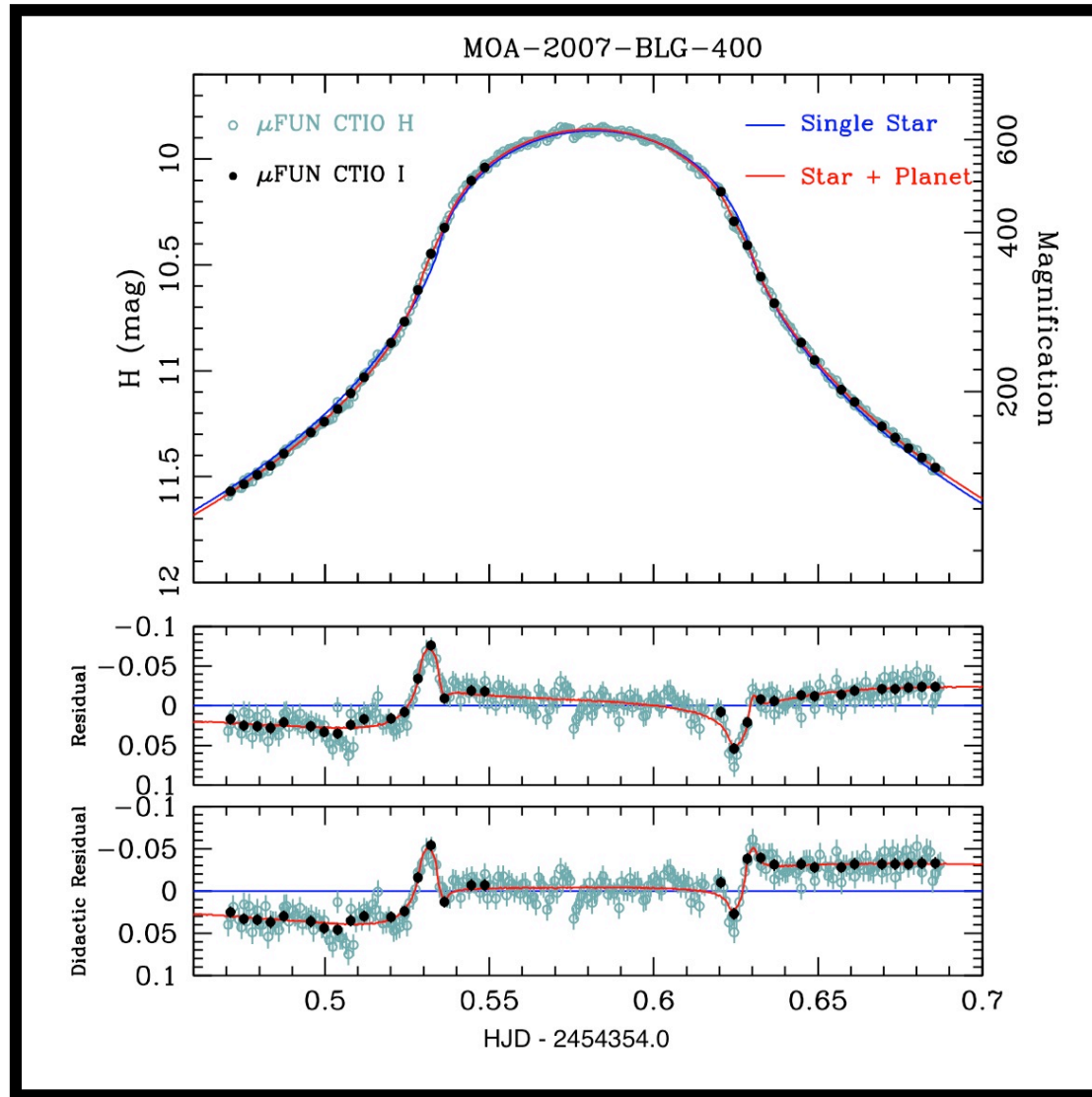
2007: "Buried" Jupiter-mass planet, exhumed by Dong et al. (2008)
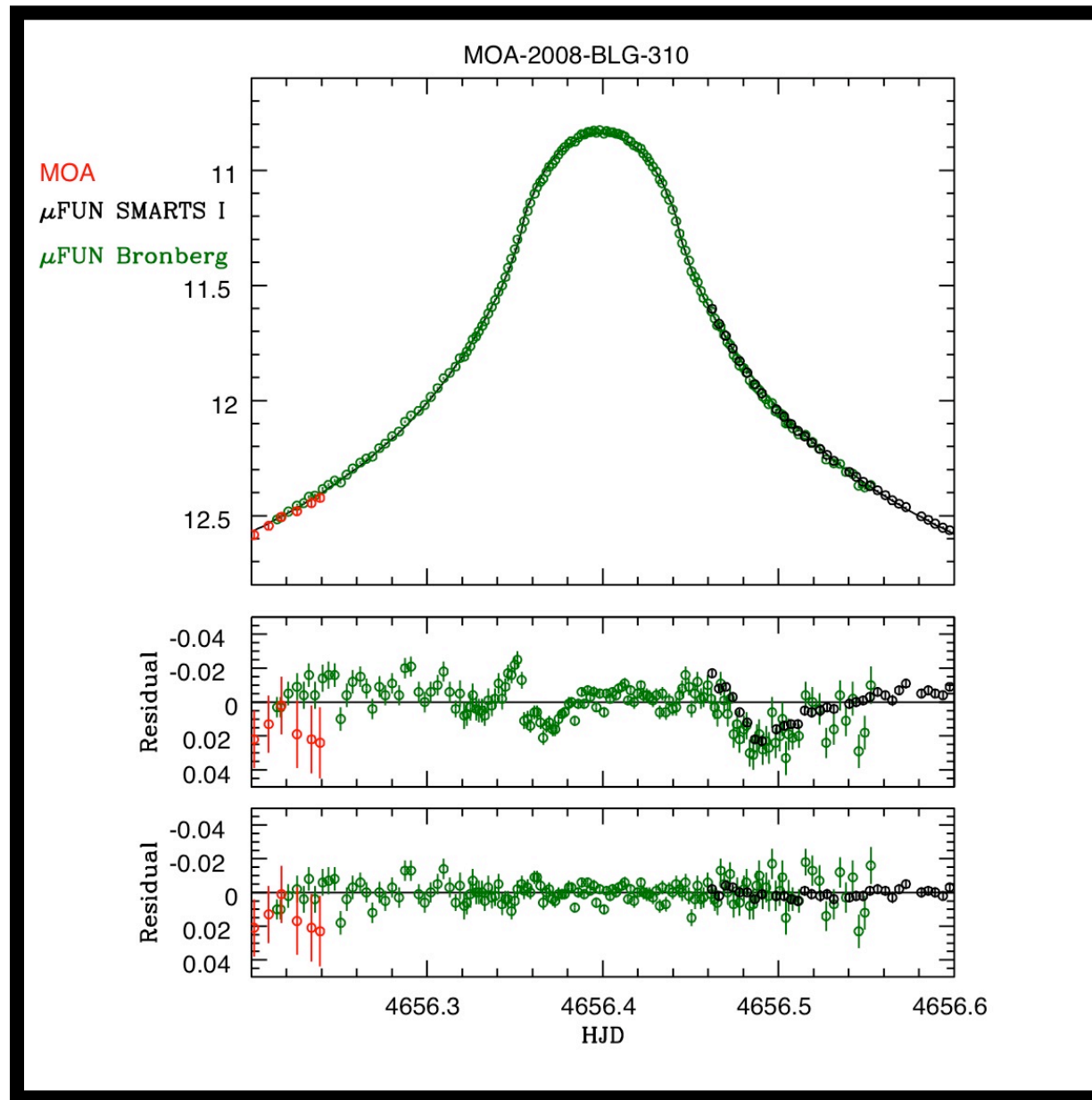
2008: "Buried" Saturn-mass planet, likely in the bulge.
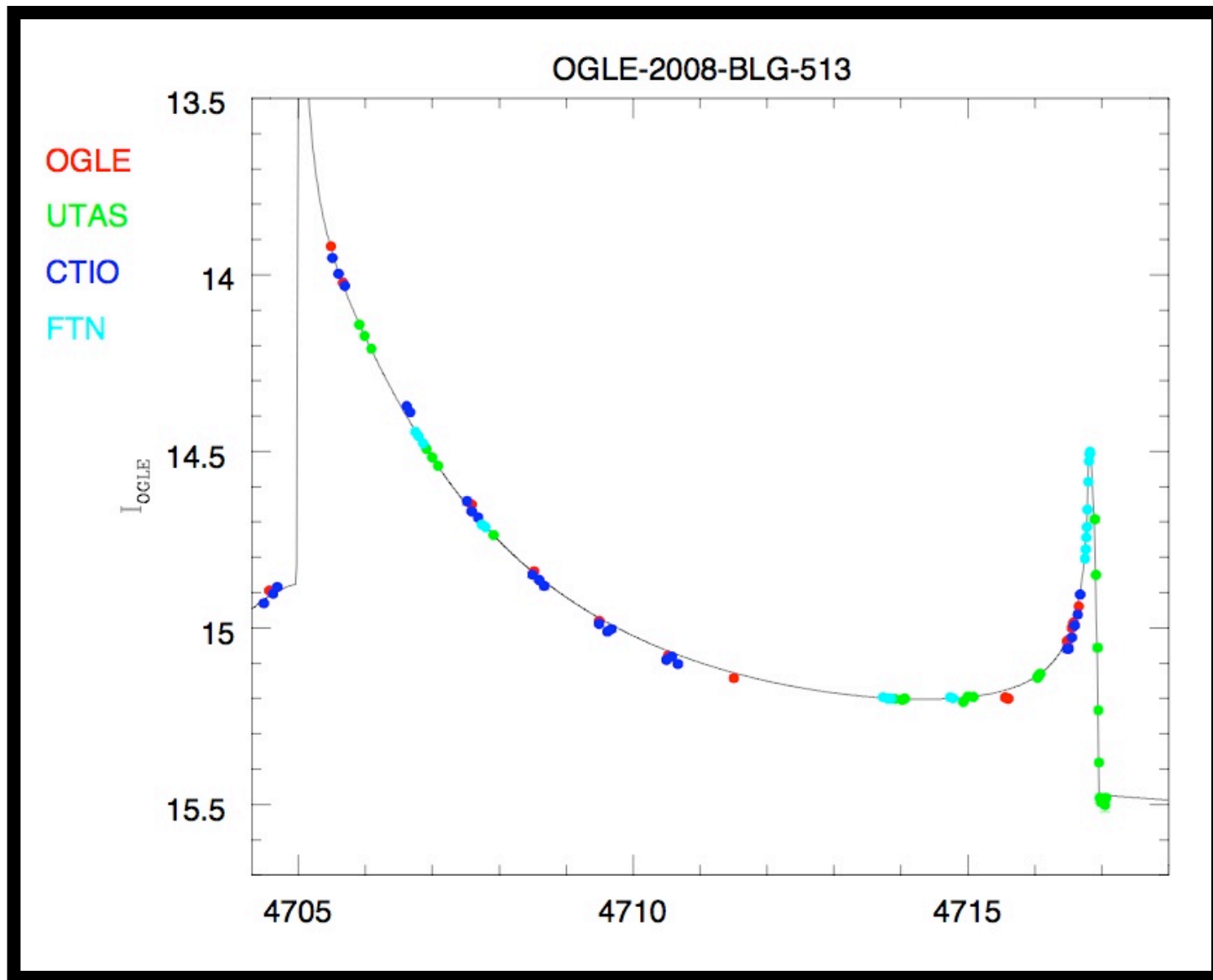
2008: Brown dwarf companion?

More on the Way…

- **Eight likely planets discovered in the 2007-2008 seasons.**

- **14 likely planets discovered to date, in 12 systems.**

- **2009 season underway (possible detection of a Jupiter-mass planet by MOA)**

- Can expect ~4 planets per year.

What's Next?

- **Current setup (alert/follow-up) saturated**
  - Nearly all of the useable bulge monitored
  - Many events cannot be monitored
  - Monitoring one event at a time too inefficient

- **A new strategy**
  - Dispense with alert/follow-up
  - Simultaneously detect and monitor microlensing events

What is Required?

- **Event Rate**

  - Primary Event Rate

  $$\Gamma \approx 10^{-5}\, \text{yr}^{-1}$$

  - Detection Probability

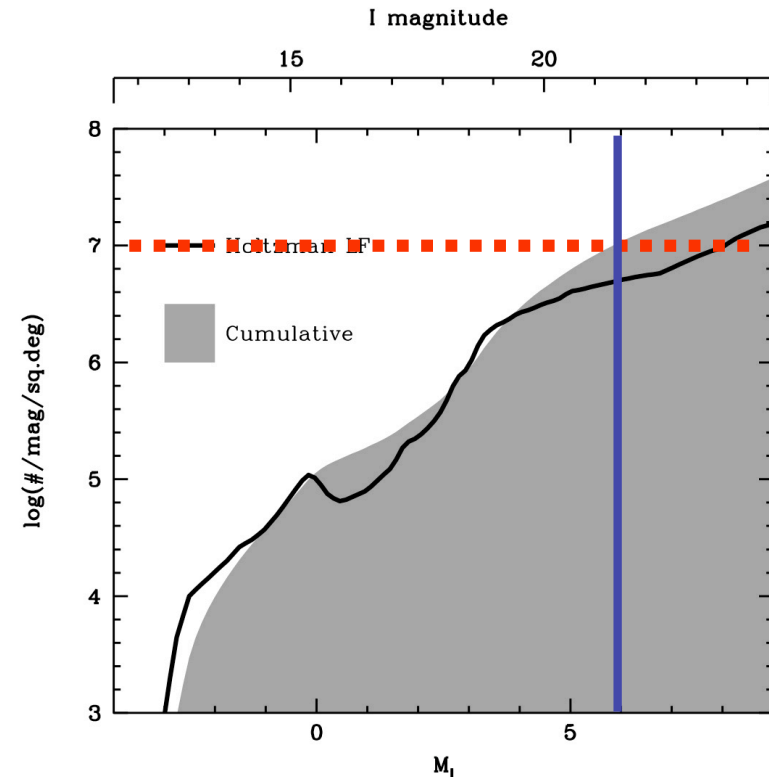 $$P \approx A_0 \theta_p \approx 1\% \left(\frac{M_p}{M_{Earth}} \right)^{1/2}$$

  - Detections Per Year

$$N \approx n_F \Omega \Phi \Gamma P \approx 10\ \text{yr}^{-1} \left(\frac{\Omega}{10\square°} \right) \left(\frac{\Phi}{10^7\, /\square°} \right) \left(\frac{\Gamma}{10^{-5}\, \text{yr}^{-1}} \right) \left(\frac{P}{1\%} \right)$$

What is Required?

Detecting the Perturbations from Earth-mass Planets

- Sampling rate ~ 10 minutes

$$t_{E,p} = 2\text{hrs}\left(\frac{M_p}{M_E}\right)^{1/2}$$

- Photometric Accuracy ~ 1% at I~21

  – Signal Magnitude

$$\frac{\Delta F}{F} \approx 1\%\left(\frac{M_p}{M_\mars}\right)\left(\frac{R_*}{R_\odot}\right)^{-2}$$

  – Photometric Uncertainty

$$\sigma = 1\%\left(\frac{D}{2\text{m}}\right)^{-1}\left(\frac{t_{\exp}}{120\text{s}}\right)^{-1/2} 10^{0.2(I-21)}$$

NextGen μLensing Survey

- Requirements to detect ~10 Earth-mass planets per year:

  - Monitor ~10 square degrees of the Galactic bulge continuously with ~10 minute sampling using 1-2m class telescopes, distributed longitudinally throughout the southern hemisphere.

  - Large FOV (2-4 square degree) cameras needed.

Expected Results
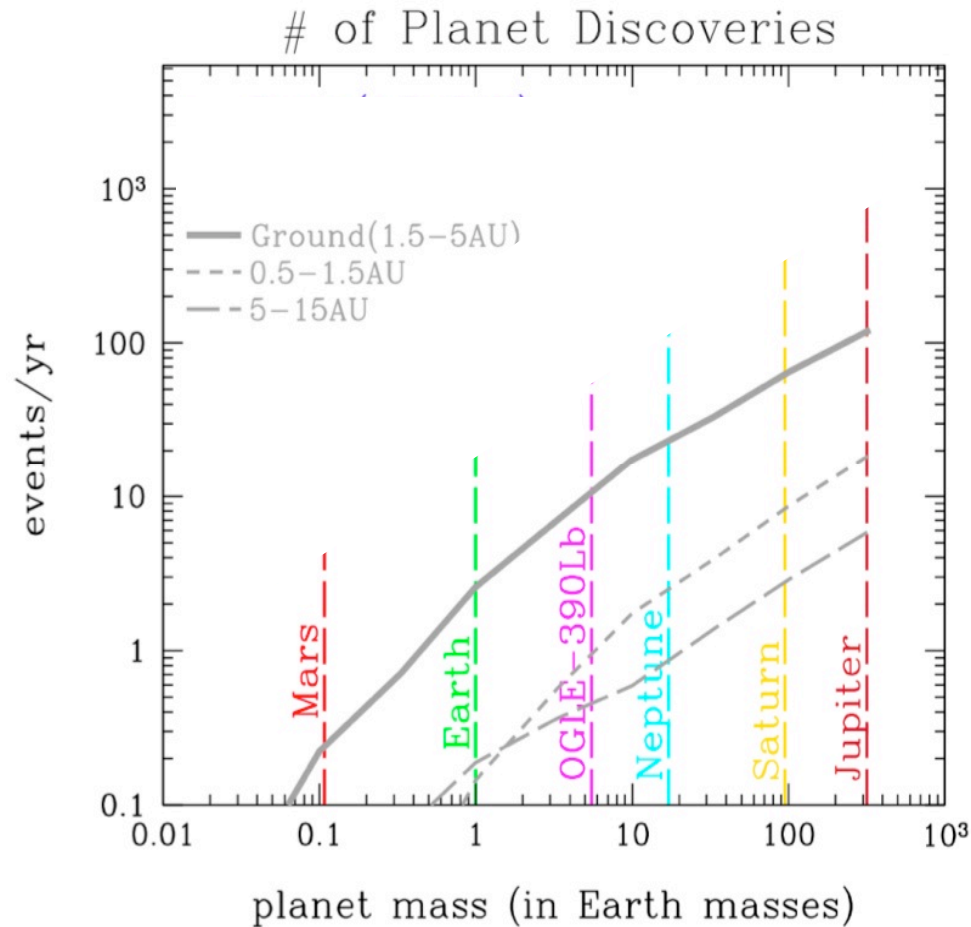
A next-generation ground-based µlensing survey can test planet formation by probing planets with M>M$_\oplus$ beyond the snow-line.

Spontaneous Generation

- MOA-II (NZ, currently operating)
  - 1.8m telescope, 2.18 sq. degree camera
- OGLE -IV (Chile, 2010)
  - 1.3m telescope, upgrade to 1.4 sq. degree camera
- All that is needed is a 1-2m telescope with a large FOV in South Africa.

"Recommendation A. II. 1 Increase dramatically the efficiency of a ground-based microlensing network by adding a single 2 meter telescope."

Korean Microlensing Telescope Network (KMTNet)

- A ~30 Billion Won Korean initiative recently been approved by the Korean government (Byeong-Gon Park PI).
  - Three telescopes:
    - South Africa
    - Chile
    - Australia

Technology

- Ground-based 1-2m, Wide FOV Telescope
  - Several very similar telescopes already operating
    - MOA-II
    - Pan-STARRS-1 - $20M
- Space-based microlensing mission
  - Requires almost no technology development.
  - Can extensively leverage other missions (Spitzer, NextView, Ikonos, JWST)
  - Can use many components that are demonstrated on orbit or flight qualified.

Modeling Challenges

- Discovery rate is currently being limited by modeling and manpower.
- Next-generation surveys will exacerbate this problem severely.
  - Order of magnitude larger detection rate.
- Need:
  - More hands (training).
  - Development of automated analysis software.

Summary

- Ground-based Next-Generation Survey:
  - Support for analysis and software development.
  - Frequency of planets $> M_\oplus$ beyond the snow line.
  - Test planet formation theories.

- **Either:** Space-based Microlensing Mission: +$300M + launch
  - Complete census of planets with mass greater than Mars and $a > 0.5$ AU.
  - Sensitivity to all Solar System planet analogs except Mercury.
  - Demographics of planetary systems - tests planet formation theories.
  - Detect "outer" habitable zone (Mars-like orbits) where detection by imaging is easiest.
  - Can find moons and free floating planets.

- **Or:** Joint μlensing/Dark Energy Mission   +$100M—$200M?
- Total cost to "Exoplanet Community": **$100M—$400M**